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Cyclone separation in a supercritical water circulating fluidized bed reactor for coal/biomass gasification: Structural design and numerical analysis

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ABSTRACT

A new concept of a supercritical water (SCW) circulating fluidized bed reactor is proposed to produce hydrogen from coal/biomass gasification. The cyclone is a key component of the reactor system. In this paper, cyclones with a single circular inlet (SCI) or a double circular inlet (DCI) were designed to adapt to the supercritical conditions. We evaluated the separation performance of the two cyclones using numerical simulations. A three-dimensional Reynolds stress model was used to simulate the turbulent flow of the fluid, and a stochastic Lagrangian model was used to simulate the particle motion. The flow fields of both cyclones were three-dimensionally unsteady and similar to those of traditional gas–solid cyclones. Secondary circulation phenomena were discovered and their influence on particle separation was estimated. Analyzing the distribution of the turbulence kinetic energy revealed that the most intensive turbulence existed in the zone near the vortex finder while the flow in the central part was relatively stable. The particle concentration distribution was non-uniform because of centrifugal forces. The distribution area can be divided into three parts according to the motion of the particles. In addition, the separation efficiency of both cyclones increased with the inlet SCW velocity. Because of its perturbance flow, the DCI separator had higher separation efficiency than the SCI separator under comparable simulations. However, this was at the expense of a higher pressure drop across the cyclone.

Introduction

The extensive consumption of fossil fuels continues to generate problems related to environmental pollution and the exhaustion of finite energy resources, making it imperative to develop alternative energy sources. Hydrogen, with its environmentally friendly combustion product and high energy content, is gaining increasing attention worldwide. Supercritical water gasification (SCWG) is a promising and potentially clean technology that can produce hydrogen from coal and biomass that avoids the energy-intensive drying process associated with conventional production (Kruse & Gawlik, 2003). In the past two decades, tubular reactors have been employed by most researchers to investigate SCWG (Antal, Allen, Schulman, Xu, & Divilio, 2000; Guo et al., 2012; Lu et al., 2006; Lu, Guo, Zhang, & Yan, 2007). To solve the problem of plugging that often occurred in tubular reactors, a supercritical water (SCW) fluidized bed was proposed (Matsumura & Minowa, 2004). In 2008, a SCW fluidized bed that gasified biomass was successfully developed in our laboratory (Lu et al., 2008). The SCW fluidized bed has also been proven as an economic and effective reactor for the gasification of coal and organic sludge (Chen, Zhang, Gao, & Li, 2017; Korzh & Bortyshevskyi, 2016; Meng et al., 2016).

To develop our understanding and optimize the design of this SCW fluidized bed, the hydrodynamic and heat transfer characteristics, and the coal/biomass gasification process were studied experimentally and numerically by our group (Lu et al., 2013; Lu, Huang, & Zheng, 2014; Lu, Huang, Zheng, & Jing, 2015; Lu, Zhang, & Dong, 2016; Su, Jin, Guo, & Guo, 2015; Wei & Lu, 2016). Despite its advantages, testing with the SCW fluidized bed revealed several operational issues, which included low product capability, low contact efficiency, and a difficulty in scaling up the reactor. Thus, inspired by developments in traditional gas–solid fluidized beds, our group proposed a SCW circulating fluidized bed (CFB). In a SCW CFB gasifier, solid particles are continuously fed into the bottom of the riser and the solids entrained by the SCW flow are captured

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Nomenclature

C	Cunningham's correction factor
C_D	Drag coefficient
d	Particle diameter, m
$\bar{d}$	Characteristic diameter, m
d_{50}	Cut-point particle diameter, m
F_k	Momentum transport coefficient, t^{-1}
g	Gravity acceleration, m/s^2
m	Particle mass flow rate, kg/s
n	Distribution parameter
P	Pressure, Pa
r_p	Radius of particle, m
Re	Reynolds number
$Stk_{0.5}$	Cut-point Stokes number
t	Time, s
u	Instantaneous velocity, m/s
u'	Dispersion velocity, m/s
$\bar{u}$	Time average velocity in axial direction, m/s
u_p	Particle instantaneous velocity in axial direction, m/s
v_p	Particle instantaneous velocity in radial direction, m/s
$\bar{v}$	Time-averaged velocity in radial direction, m/s
w_p	Particle instantaneous velocity in tangential direction, m/s
$\bar{w}$	Time-averaged velocity in tangential direction, m/s
x	Axial distance, m
δ	Kronecker factor
μ	Fluid velocity, kg/(m s)
ρ	Density, kg/m^3

Subscripts

f	Fluid
i, j, k	1, 2, 3
in	Inlet
p	Particle
t	Tangential direction

at the top and returned to the bottom via a recirculation system on the outside of the riser that maintains circulation of solids. The benefits of CFB reactors include significantly lower back-mixing of gases and solids, improved contact efficiency and a higher product capacity on account of it being a continuous process (Wang & Zhu, 2016). A CFB system typically contains a riser, a cyclone, a standpipe, and a solids return. The cyclone is a key unit in the CFB and its performance is critical to the unit's safe and stable operation.

Cyclone separators have been widely used in many industrial processes because of their relative simplicity to fabricate, low operating costs and adaptability to harsh operating conditions. The literature includes a large number of investigations into traditional gas–solid cyclones (for example, Bernardo, Mori, Peres, & Dionisio, 2006; Haig, Hursthouse, Sykes, & Mcilwain, 2016; Sgrott, Noriler, Wiggers, & Meier, 2015; Shin, Kim, Jang, Chung, & Bohnet, 2005; Surmen, Avci, & Karamangil, 2011; Zhao, Shen, & Kang, 2004), but little work has focused on cyclones used for SCW–solid separation at extremely high pressures and temperatures. Chu, Wang, Xu, Chen, and Yu (2011) developed a CFD–DEM model to describe the gas–solid flow in a typical Lapple cyclone and successfully captured the separator's key features such as the pressure drop, velocity distribution, and particle flow pattern at different solid-loading ratios. Shi, Bayless, Kremer, and Stuart (2006) carried out a simulation to predict the pressure drop and velocity profiles in cyclones operated at high temperatures and pressures. They found that density had a significant effect on the pressure distribution whereas this was only negligibly affected by viscosity. Furthermore, density and viscosity were found to have similar impacts on velocity. Besides conventional tangential inlet cyclones, novel cyclone separators have been developed for special conditions (Chen, Liu, & Gong, 2017; Paiva, Salcedo, & Araujo, 2010; Shi, Wei, & Chen, 2013; Xu, Li, Wang, & Jin, 2016; Zhang, Wang, & Jin, 2013). Cui, Chen, Gong, and Yu (2010) introduced a radial-inlet cyclone for an opposed multi-burner gasification system and simulated the gas–particle flow field, comparing the detailed information obtained with that from a traditional cyclone. Qian and Wu (2009) numerically studied the gas-flow fields and separation performance for different angles of the inlet section and concluded that an inlet angle of 45° produced the lowest pressure drop and highest separation efficiency. Notably however, all of the cyclones thus far mentioned cannot be applied to effectively separate particles from the SCW flow in a SCWG. Instead, a new type of cyclone that can withstand the extremely harsh conditions needs to be specifically designed.

In this study, two cyclones are specifically designed to suit supercritical conditions. We then evaluate their separation performance by numerical simulation. The distributions of pressure and velocity in the cyclones are obtained and analyzed. Secondary circulation phenomena are categorized into three types with the influence of each on particle separation then estimated. Additionally, the radial particle-concentration distribution was studied. The trajectories of differently sized particles are shown and the change in location of groups of particles over time is presented. Finally, the two most important cyclone parameters, the pressure drop and separation efficiency, are discussed.

Structural design of the cyclones

A cyclone's operating conditions are determined by those of the riser. SCW was employed as the fluid phase. SCW has distinct physical properties compared with those of water vapor or liquid water. Fig. 1 shows the variations in key physical properties with temperature at a pressure of 23 MPa. In the vicinity of the critical temperature, Fig. 1 shows that the properties vary significantly despite only small changes in temperature. The working conditions of this study were set as 873 K and 30 MPa, yielding a SCW density and viscosity of 77.27 kg/m^3 and 34.75 μPa s, respectively (Lu et al., 2016). The SCW density is much larger than that of water vapor though the viscosity is only slightly higher. The inlet SCW velocity to the riser was constrained within the range of 0.3–0.8 m/s to ensure the steady fast fluidization in the riser. In this way, the inlet flow rate to the cyclone was determined.

The density of coal/biomass was relatively low, which caused difficulties in the formation and steady operation of fast fluidization (Wang & Zhu, 2016). Thus, quartz sand (density of 2500 kg/m^3)

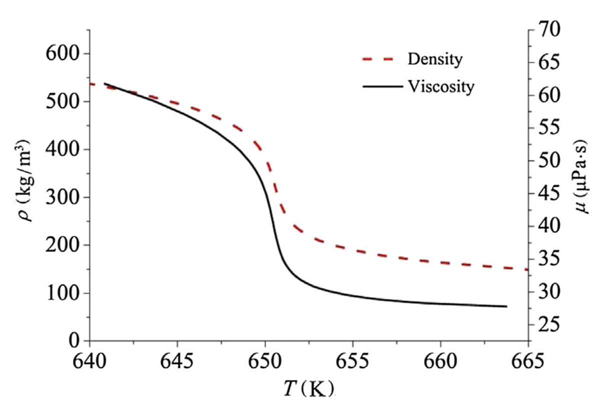

Fig. 1. Density and viscosity of supercritical water near the critical point at 23 MPa.

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